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EARLY HIERARCHICAL FORMATION OF MASSIVE GALAXIES TRIGGERED BY INTERACTIONS

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ABSTRACT

To address the problem concerning the early formation of stars in massive galaxies, we present the results of a semi-analytic model of galaxy formation which includes a physical description of starbursts triggered by galaxy interactions. These originate from the destabilization of cold galactic gas occurring in galaxy encounters, which in part feeds the accretion onto black holes powering quasars, and in part drives circumnuclear starsbursts at redshifts $z \approx 2-4$, preferentially in massive objects. This speeds up the formation of stars in massive galaxies at high redshifts without altering it in low mass galactic halos. Thus, at intermediate $z \approx 1.5-2$ we find that a considerable fraction of the stellar content of massive galaxies is already in place, at variance with the predictions of previous hierarchical models. The resulting high-z star formation rate and B-band luminosity functions, and the luminosity and redshift distribution of galaxies in K-band at $z \lesssim 2$ are all in good agreement with the existing observations concerning the bright galaxy population.

Subject headings: galaxies: formation — galaxies: high-redshift — galaxies: interactions

1. INTRODUCTION

Current hierarchical theories of galaxy formation envisage the build up of stars in galaxies as a gradual process driven by the continuous growth of the host dark matter (DM) galactic halos through repeated merging events. These progressively increase also the gas mass in the growing galaxies; its subsequent radiative cooling is partially counteracted by the heating due to the winds from Supernovae originated by parent massive stars. The net result of such a "quiescent" star formation is a gradual increase of the stellar content of the galaxies.

But when the picture is quantitatively modeled through the semi-analytic models (SAMs, Kauffmann et al. 1993; Somerville & Primack 1999; Cole et al. 2000; Menci et al. 2002) the resulting amount of stars formed at high z in the *bright* galaxy population is lower than indicated by several observational results.

Among these we mention first the excess of the cosmic density of bright galaxies observed to be in excess over the model predictions at $z \approx 3-5$. True that several groups (e.g., Cole et al. 2000; , Somerville Primack & Faber 2001; Fontana et al. 2003a) have shown the canonical SAMs (i.e., with no merging-induced starbursts) to provide a total star formation history (integrated over all luminosities) consistent with observations. But when one focuses on the UV luminosity density produced by the *brightest* galaxies only, these SAMs underpredict the luminosity densities observed at $z \gtrsim 4$ (Fontana et al. 1999, 2003a). This traces back to the fact that the detailed shape of the luminosity functions (LFs) from SAMs are appreciably steeper than the observed ones at these redshifts. Actually, the SAMs overpredict the number of faint galaxies and, for the canonical SAMs with quiescent star formation only, they underpredict the bright ones, see Somerville, Primack & Faber (2001).

Second, and most important, the SAMs underpredict both the bright galaxies observed in the K-band luminosity functions at intermediate redshifts ($z \approx 1-2$, see Pozzetti et al. 2003) and the galaxies brighter than $K = 20$ counted at $z > 1.5$ (Cimatti et al. 2002). The emission in the K-band is largely contributed by old stellar populations, and so is a measure of the amount of stars already formed; thus the above observations imply that the star content of massive galaxies already in place at $z \approx 2$ is larger than that resulting from the gradual star formation typical of hierarchical models. Indeed, independent, direct observations at $z \approx 2$ of the stellar mass density of massive galaxies (in the range $m_* \approx 10^{10} - 10^{11}\ M_\odot$) yield a fraction close to 0.3 of the present value, while the canonical (no-burst) SAMs yield a fraction around 0.1 (see Fontana et al. 2003b). The above results concur to indicate that the physics of hierarchical galaxy formation still lacks some basic process enhancing star formation in massive galaxies.

A candidate for such an enhancement is constituted by starbursts triggered by galaxy interactions, as proposed by Somerville, Primack & Faber (2001), see also Cavaliere & Menci (1993). The former authors assumed that satellite galaxies contained in the same host DM halo (i.e., in groups or clusters of galaxies) may undergo binary aggregations, which would not only affect their mass distribution but also brighten them by triggering starbursts. In such a model, only encounters leading to outright merging are considered; in addition, the fraction of galactic gas converted into stars during each burst is taken to be constant in time, with a parametrized dependence on the merger mass ratio which favors major mergers. The resulting starbursts, while improving the match with the observed UV LFs at $z = 3$ and $z = 4$, still do not provide enough high-z star formation to account for the number of bright ($K > 20$) galaxies at $z > 1.5$ observed by Cimatti et al. (2002).

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Thus one main problem with the current SAMs is their failure to form enough stars at high-z in *bright* galaxies, so as to match the observed bright end of the K-band LFs at intermediate z.

Here we address the issue on the basis of a more complete description of the starbursts triggered by galaxy encounters. This is based on the physical model for the destabilization of cold galactic gas during galactic merging and fly-by developed by Cavaliere & Vittorini (2000, CV00). The destabilized gas is assumed to feed in part the accretion onto a central super-massive black hole (BH) so powering quasar-like emission, and in part a burst of star formation. The amount of destabilized gas, the duration of the bursts, and their rate set by the galaxy encounters are determined by the physical properties of the galaxies and of their host halos, groups or clusters. While CV00 adopted simplified derivations for the galactic properties in common DM halos, here such properties are self-consistently computed from the SAM presented in Menci et al. (2002).

In a previous paper (Menci et al. 2003) we have shown that the quasar (QSO) evolution resulting from such a model is in excellent agreement with a whole set of observables. Here we focus on the circumnuclear starbursts originating from the fraction of cold gas destabilized in galaxy encounters complementary to the gas accreted to the central supermassive BH; such starbursts mainly affect the massive galaxy population.

We recall in Sect. 2 the basic features of the SAM presented in Menci et al. (2002), while in Sect. 3 we present our treatment of the new processes included in our present model, i.e., the fly-by events and the associated destabilization of cold galactic gas. The results are presented in Sect. 4, while Sect. 5 is devoted to conclusions and discussion.

2. MODELING THE GALAXY EVOLUTION

To describe the galaxy evolution in the hierarchical scenario, we adopt the SAM described in detail in Menci et al. (2002); here we recall the basic points. We consider both the host DM halos containing the galaxies (i.e., groups and clusters of galaxies with mass M, virial radius R and circular velocity V), and the DM clumps (with mass m, radius r and circular velocity v) associated with the individual member galaxies. The former grow hierarchically to larger sizes through repeated merging events (at the rate given in Lacey & Cole 1993), while the latter may coalesce either with the central galaxy in the common halo due to dynamical friction, or with other satellite galaxies through binary aggregations. The timescale for the dynamical friction and the binary merging processes, and so the probability for such processes to occur in each timestep, are given by eq. (2) and (4) in Menci et al. (2002).

We assume initially (at $z \approx 10$) one galaxy in each host structure, with the latter following the Press & Schechter mass distribution. The probability for the merging processes (dynamical friction and binary aggregations) to occur during the hierarchical growth of the hosting structure yields the differential distribution function $N(v, V, t)$ of galaxies with given v in hosts with circular velocity V at the cosmic time t. From $N(v, V, t)$ we derive the number $N_T(V, t)$ of galaxies in a host halo (membership), and the overall distribution of galaxy circular velocity $N(v, t)$ irrespective of the host.

The properties of the baryons (gas and stars) contained in the galactic DM clumps are computed as follows. Starting from an initial amount $m\,\Omega_b/\Omega$ of gas at the virial temperature of the galactic halos, we compute the mass m_c of cold baryons within the cooling radius. The disk associated to the cold baryons will have a radius $r_d(v)$, rotation velocity $v_d(v)$, and dynamical time $t_d = r_d/v_d$, all computed after Mo, Mao & White (1998). From such a cold phase, stars are allowed to form at the rate

$$\dot{m}_* = \frac{m_c}{t_{dyn}} \left(\frac{v}{200\,\mathrm{km\,s^{-1}}} \right)^{-\alpha_*} \tag{1}$$

Finally, a mass $\Delta m_h = \beta\, m_*$ is returned from the cool to the hot gas phase due to the energy fed back by canonical type II Supernovae associated to m_*; the feedback efficiency is taken to be $\beta = (v/v_h)^{\alpha_h}$. The values adopted for the parameters $\alpha_* = -1.5$, $\alpha_h = 2$ and $v_h = 150$ km/s fit both the local B-band galaxy LF and the Tully-Fisher relation, as illustrated by Menci et al. (2002).

At each merging event, the masses of the different baryonic phases are refueled by those in the merging partner. The further increments Δm_c, Δm_*, Δm_h from cooling, star formation and feedback are recomputed on iterating the procedure described above.

Thus, for each galactic v, the star formation defined by eq. (1) is driven by the cooling rate of the hot gas and by the rate of refueling of cold gas, which in turn is related to the progressive growth of the total galactic mass along the merging tree. The related brightening of galaxies is a gradual process, and the associated star formation history is often referred to as "quiescent" star formation.

The integrated stellar emission $S_\lambda(v, t)$ at the wavelength λ is computed by convolving the SFR with the spectral energy distribution ϕ_λ obtained from population synthesis models:

$$S_\lambda(v, t) = \int_0^t dt'\, \phi_\lambda(t - t')\, \dot{m}_*(v, t')\ . \tag{2}$$

In the following we adopt ϕ_λ taken from Bruzual & Charlot (1993), with a Salpeter IMF. The dust extinction is computed as described in Menci et al. (2002).

All computations are made in a Λ-CDM cosmology with $\Omega_0 = 0.3$, $\Omega_\lambda = 0.7$, a baryon fraction $\Omega_b = 0.03$, and Hubble constant $h = 0.7$ in units of 100 km s^{-1} Mpc^{-1}.

3. STAR FORMATION TRIGGERED BY GALAXY ENCOUNTERS

In the present work, we upgrade the above model by adding a treatment of fly-by events (i.e., encounters which do not lead to bound merging) and of the related bursts of star formation. Indeed, galaxy encounters are expected to destabilize part of the available cool gas by causing it to loose or transfer angular momentum (Barnes & Hernquist 1998; Mihos 1999); this triggers gas inflow. The gas funneled inward may end up in accretion onto a central supermassive BHs, but also in a nuclear starburst (see Sanders & Mirabel 1996). A quantitative model to derive the fraction f of cold gas destabilized by the encounters has been worked out by CV00; here we recall the guidelines in terms suitable for direct implementation in our SAM.

The fraction of cold gas which is destabilized in each interaction event and feeds the starbursts is derived from eq. A3 of CV00 in terms of the variation Δj of the specific angular momentum $j \approx Gm/v_d$ of the gas; in slow, grazing encounters between galaxies with relative velocity V_r one obtains:

$$f(v,V) \approx \frac{3}{8}\Big|\frac{\Delta j}{j}\Big| = \frac{3}{8}\Big\langle\frac{m'}{m}\,\frac{r_d}{b}\,\frac{v_d}{V_r}\Big\rangle . \quad (3)$$

The effective impact parameter $b = max[r_d, \overline{d}(V)]$ is the maximum between the radius r_d and the average distance $\overline{d}(V) = R/N_T^{1/3}$ of the galaxies in the halo; we take V_r to be twice the one-dimensional velocity dispersion $\sigma_V = V/\sqrt{2}$ of the host halo. The first approximate equality is derived by considering the amount of gas which is in centrifugal equilibrium outside a circumnuclear region of fixed size; since the extension Δr of the outer region is proportional to j (see, e.g., Mo, Mao & White 1998), a loss of angular momentum implies a negative Δr and hence a mass flow toward the circumnuclear region. As for the prefactor, it accounts for the probability 1/2 of inflow rather than outflow related to the sign of Δj. We assume that 1/4 of the inflow feeds the central BH, while the remaining fraction is assumed to kindle circumnuclear starbursts, see Sanders & Mirabel (1996); thus, the starbursts efficiency f in eq. (3) is three times larger than the complementary BH accretion efficiency shown in fig. 1 of Menci et al. (2003).

The last equality in eq. (3) has been derived by CV00 by computing the variation $\Delta j = Gm' r_d/Vb$ of the angular momentum in the galaxy from the gravitational torque (proportional to the disk size r_d) exerted by the partner galaxy with mass m'; this is time-integrated along the partner orbit. Note that the dependence of Δj on r_d causes the the amount of destabilized gas to be larger in more massive systems. The average runs over the probability of finding a galaxy with mass m' in the same halo V where the galaxy m is located.

When inserted into our SAM and applied to the BH accretion and to the related QSO emission (Menci et al. 2003), the above model has proven to be very successful in reproducing the observed properties of the QSO population from $z = 6$ to the present, including the rapid decline of their densities from $z \approx 2.5$ to $z = 0$ and even the detailed changes of their LF from $z \approx 5$ to $z = 0$. In the present picture, the interaction-driven starbursts constitute the "counterpart" of the BH accretion powering the QSOs.

To compute the average effects of the cold gas destabilization on the star formation rate and hence on the galactic emission, we derive the probability for a given galaxy to be in a burst phase. This is defined as the ratio τ_e/τ_r of the duration of the burst to the average time interval between bursts.

In turn, such quantities can be derived from a detailed analysis of the orbital parameters (see Saslaw 1985); following CV00, here we just recall that tides effective for angular momentum transfer (as considered in eq. 3) require two conditions: the interaction time is to be comparable with the internal oscillation time in the galaxies involved (resonance); the orbital specific energy of the partners is not to exceed the sum of the specific internal gravitational energies of the partners. The rate of such encounters τ_r^{-1} is then given by Saslaw (1985) in terms of the distance $r_t \approx 2r$; for a galaxy with given v inside a host halo with circular velocity V the result reads

$$\tau_r^{-1} = n_T(V)\,\langle\Sigma(v,V)\rangle\,V_r(V)\ , \quad (4)$$

where $n_T = 3\,N_T/4\pi R^3$, and the cross section is averaged over all partners with effective tidal radius r'_t in the same halo V. The membership N_T, and the distributions of v', r'_t and V_r are computed from the SAM described in §2.

The condition for a grazing encounter defines the encounter duration $\tau_e = \langle(r_t + r'_t)/V_r\rangle$ (with the upper limit given by τ_r in eq. 4) where the average is again over all partners with tidal radius r'_t in the same host halo V. It must be noted that the cross section in eq. (4) determines the probability for any grazing encounter including the fly-by events, which are in fact more frequent than major mergers and dominate the statistics of galaxy encounters. We also stress that in our model the eq. (4) determines only the probability τ_e/τ_r of finding a galaxy in the burst phase, but does not affect the evolution of the galaxy mass function. This is instead determined by the processes of dynamical friction and binary aggregation proper, for which we retain the cross sections given in Menci et al. (2002), and recalled in Sect. 3.

The *average* SFR associated to the destabilized cold gas during an encounter lasting a time τ_e reads,

$$\Delta\dot{m}_*(v,z) = \Big\langle\frac{f(v,V)\;m_c(v)}{\tau_e(v,V)}\Big\rangle_{\tau_e/\tau_r} . \quad (5)$$

The average is here over all host halos with circular velocity V, and is weighted with the probability τ_e/τ_r of finding the galaxy in the burst phase.

We remark that our model includes the effects of both fly-by events and bound mergings. Although the former induce starbursts with a lower efficiency ($f \approx 0.1 - 0.4$ at $z \gtrsim 3$) they contribute appreciably to the *average* star formation rate in bursts (eq. 5). In fact, the fly-by events are more probable than major mergers, and hence provide larger values for the probability τ_e/τ_r entering the average in eq. 5. This holds even though for major merging events (requiring small relative velocities and hence small values of V_r in eq. 3) the efficiency may attain values $f \approx 0.7$, consistent with the values 0.65-0.8 obtained in the hydrodynamical simulations by Mihos & Hernquist (1996), and close to the values observed in SCUBA sources and in the local Ultra Luminous Infrared Galaxies (see Blain et al. 2002 and references therein; Sanders & Mirabel 1996). At $z \gtrsim 3$, the contributions to eq. (5) from merging and from fly-by events are comparable.

The *average* contribution to the stellar emission $S(v,t)$ from bursts in a galaxy with circular velocity v at the time t is given by eq. (2), with the quiescent star formation rate $\dot{m}_*$ replaced by the starbursts rate $\Delta\dot{m}_*(v,t)$ given by eq. (5). From $S(v,t)$ we compute the LF given by $N(v,t)\,dv/dS$.

4. RESULTS

In fig. 1 (bottom panel) we show the effect of bursts on the B-band LF of galaxies at $z = 0$, and on the UV LFs $z = 3$ and at $z = 4$.

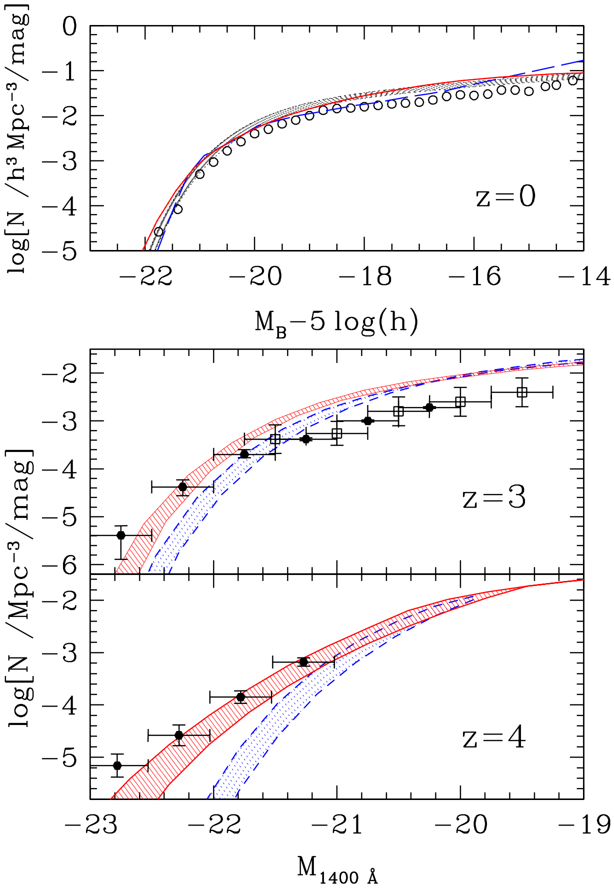

Fig. 1. - The predicted LFs of galaxies in the quiescent (blue dashed lines) and starburst modes (red solid lines) at $z \approx 0$ (in the B-band, top panel), and at $z \approx 3$ and $z \approx 4$ (at 1400 Å, middle and bottom panels, respectively). In the top panel, the shaded area corresponds to the LF measured by the Sloan Digital Sky Survey (Blanton et al. 2000), and the circles to the data from the 2dFGRS survey (Madgwick et al. 2002). In the middle and bottom panels, the two red solid lines refer to the burst model and bracket the uncertain due to different dust extinction curves (represented by the shaded regions) for given dust-to-gas ratio, see text. Similarly for the blue dashed curves (and the comprised shaded areas) referring to the quiescent model. The spectroscopic (solid squares) and the photometric (open squares) data are from Steidel et al. (1999).

As the emission in the UV (and, to a minor extent, that in the B-band) is contributed by massive, short-living stars, the LFs in fig. 1 show the effect of bursts on the instantaneous star formation at low and high redshifts. At low z (top panel) the LFs are little affected by starbursts whose effect, if anything, is to make the model LF closer to that measured by in Sloan survey (Blanton et al. 2000).

At high z, the predictions for the UV LFs are shown in the bottom panels, and compared with data uncorrected for extinction, since the dust absorption is included in the model. In particular, we implemented in our SAM the Milky Way, the Small Magellanic Cloud (SMC) and the Calzetti extinction curves, with the dust optical depth fixed by the fit to the local LF. The related uncertainties in the model predictions are illustrated by showing (for both the quiescent and the starburst modes) the brightest and the faintest LFs (corresponding to the SMC and to the Calzetti curves, respectively). Note that at high z the interactions are more effective in stimulating starbursts; at $z = 4$, compared with the quiescent mode, they brighten the galaxy LF by an amount which grows with the luminosity to reach about 0.7 mag in the brightest magnitude bin. Note also that the inclusion of bursts does not appreciably affect the LFs for galaxies fainter than $M_B \gtrsim -20$.

Indeed, burst are more efficient in high mass than in low mass systems, since the former have larger cross section for encounters (see eq. 4). In addition, in each encounter the amount of destabilized gas is larger in more massive galaxies, since the loss of angular momentum is larger for larger disks as discussed below eq. 3.

As a function of time, fig. 1 shows that galactic encounters are increasingly effective in stimulating starbursts for increasing z. In fact, the interaction rate τ_r^{-1} and the accreted fraction f decrease with increasing t, since in the growing host halos the growing membership $N_T(V)$ is offset by R, V and V_r increasing (see eqs. 3, 4). In a group, the *average* values for f drop from from a few 10^{-1} to several 10^{-3} on going from $z \approx 3$ to $z = 0$, as shown in fig. 1 of Menci et al. (2003) (the latter paper shows the efficiency for BH accretion which is three times lower than the efficiency for starbursts, as discussed below eq. 3); higher values up to $f \gtrsim 0.4$ are instead attained at $z \gtrsim 3$.

Thus, at low redshifts the lower densities and larger relative velocities of the galaxies contained in the same host environment suppress the effectiveness of the interactions and hence of the associated starbursts.

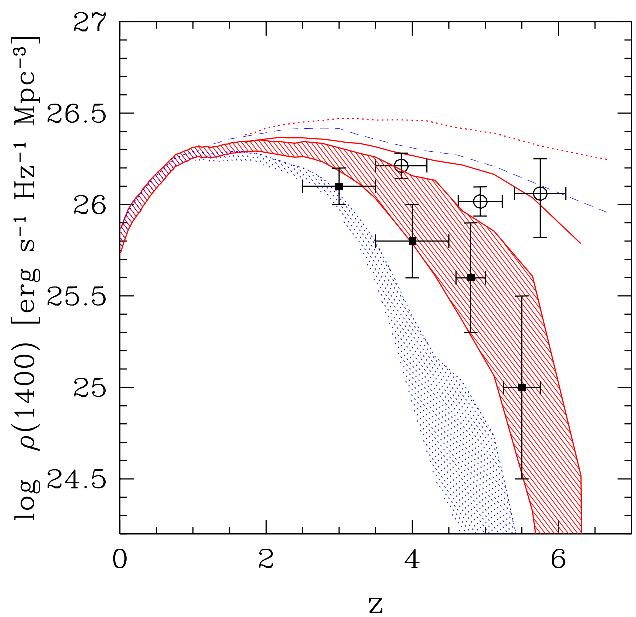

Fig. 2. - The predicted UV luminosity densities (at 1400 Å) compared with data. Solid squares refer to the data for galaxies with $m_Z < 25$ (Fontana et al. 2003a), while the shaded areas (heavy and red for the model with bursts, light and blue for the pure quiescent model) represent the model predictions – at the same limiting magnitude – adopting different extinction curves in the models (see text). In addition we plot the UV luminosity density obtained by Giavalisco et al. (2003, empty circles) by integrating the observed UV LFs down to $0.2\,L_{*3}$ (where L_{*3} is the characteristic luminosity of observed Ly-break galaxies at $z = 3$), compared with the prediction of our model for the same luminosity cut (red heavy solid line) averaged over the three extinction curves we considered in the text. We also show the total UV luminosity density in the burst (red dotted line) and quiescent (blue dashed line) models, averaged over the dust extinction as above.

Such a picture is borne out by fig. 2, where we show the effect of bursts on the cosmic UV luminosity density produced by galaxies, and compare it with existing observations. These are based on HST and VLT imaging surveys aimed at identifying high-z galaxies. The data concerning the UV luminosity density contributed by the bright ($m_Z < 25$) galaxy population are compared with the model predictions; for these we also show the uncertainties due to the different extinction curves, represented as shaded areas. In addition, we compare with the recent data from Giavalisco et al. (2003) concerning the density contributed also by fainter galaxies, with the lower limit in luminosity provided in the caption.

We note that when the UV luminosity density contributed only by bright ($m_Z < 25$) galaxies is considered, the canonical SAMs (with no bursts) underpredict the observed values. This is because such models fail to provide enough star formation to match (once dust is included) the bright end of the UV LFs at $z \gtrsim 4$ (see fig. 1). However, when one considers the total UV luminosity density (obtained by integrating the LFs over all luminosities) the same models provide a sustained luminosity density (the dashed line) up to large z. This is because the shape of the LFs from such SAMs are appreciably steeper than the observed ones at high z; while such models underpredict the density of bright sources, they overpredict the number of faint galaxies. The two effects balance as to yield a sustained total UV luminosity density at high z, as shown in fig. 2.

On the other hand, the burst model naturally provides more star formation in massive galaxies and so matches in detail the observed UV luminosity density from bright galaxies with $m_Z < 25$. We also compare our burst model with the observed UV luminosity density contributed by fainter galaxies. Following the discussion above, any such comparison depends critically on the lower luminosity limit for the integration of the UV LFs. So in comparing our prediction (heavy solid line in fig. 2) with the data from Giavalisco et al. (2003) we adopt the same luminosity cut used by such authors (see caption), finding a good agreement with observations.

As a result, in the starburst scenario the fraction of stars predicted to be already formed in *massive* galaxies by $z \approx 2$ is significantly larger then in the quiescent models. This, in turn affects the galaxy LFs and the corresponding redshift distributions in the K band; here the emission is largely contributed by evolved stellar populations, so probing the total amount of stars which have been assembled in galaxies by a given cosmic time. In the following, we shall focus on such issues since, as we recalled in Sect. 1, matching the K-band observables and the stellar mass density at intermediate redshifts constitutes one main problem for canonical SAMs.

In fig. 3 we compare the results with observations obtained from the K20 survey (Cimatti et al. 2002; Pozzetti et al. 2003). The starbursts brighten the LF by ~ 0.5 mag at $z \approx 1.5$, so matching the observed shape of the LFs (top panel). Meanwhile the faint end of the LFs is left almost unchanged. This is again a consequence of the larger effectiveness of the bursts in more massive galaxies, which is due to the physics of interaction-driven bursts combining with the statistics of encounters. On the one hand, in each bursts galaxies with larger disk sizes undergo larger losses of angular momentum as a consequence of larger gravitational torques, as explained below eq. (3); on the other hand, larger galactic sizes favor the encounters, as described in detail below eq. (4). Correspondingly, the burst model *matches* the observed number of luminous ($m_K < 20$) galaxies at $z \gtrsim 1.5$, while the quiescent model underpredicts the number by a factor $\sim 3-4$ (see bottom panel in fig. 3).

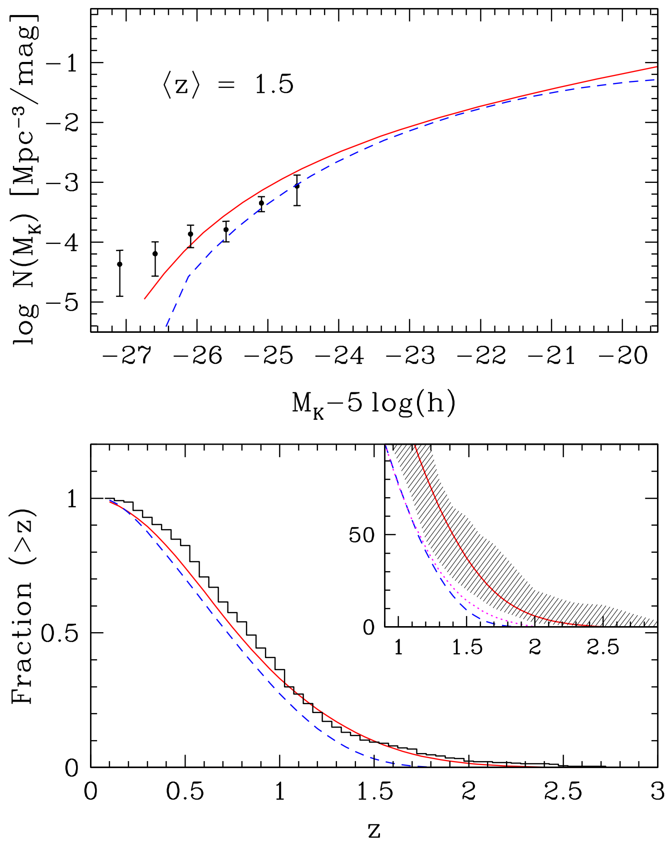

Fig. 3. - Upper panel: the K-band galaxy LFs at $z = 1.5$ in the quiescent (blue dashed line) and in the starburst model (red solid line) are compared with the data from the K20 survey (Pozzetti et al. 2003). Bottom panel: the corresponding cumulative z-distribution of $m_K < 20$ galaxies are compared with observations from the K20 survey (Cimatti et al. 2002). The inset shows in detail the cumulative distribution in the range $1 < z < 3$ with the 3σ Poissonian confidence region (shaded area); the dotted line reproduces from Cimatti et al. (2002) the prediction of the SAM by Somerville, Primack, & Faber (2001).

Inspection of fig. 3 shows that our burst model provides a better fit to the observed z-distribution of galaxies with $m_K < 20$ than the SAM by Somerville, Primack e Faber (2001), which also included starbursts. The reason is that our model provides a higher star formation rate at high redshift. This is shown by the dotted line in fig. 2; when the total UV luminosity density of our model is converted to a total density of star formation, the resulting star formation rate is larger than the Somerville, Primack & Faber (2001) rate at $z > 4$ for any reasonable dust extinction adopted in the conversion. The improvement is achieved despite of an *average* value of the burst efficiency f somewhat lower than adopted by Somerville, Primack e Faber (2001).

Our improvement is due to two circumstances. First, the above authors associate starbursts only to bound mergers; for such events (requiring very slow encounters with small V_r) we obtain from eq. (3) values $f \approx 0.7$ comparable to theirs, as these particular interactions are maximally effective in inducing loss of gas angular momentum. However, in our model we also consider the effect of the more frequent fly-by events not leading to outright merging of the involved galaxies. These produce starbursts with a lower efficiency $f \approx 0.1 - 0.4$ (at $z \gtrsim 3$), but dominate the encounter statistics. While they yield a low average f, the key quantity for Δm_* is instead the product $f\,\tau_r^{-1}$ (i.e., the efficiency weighted with the interaction rate) which is enhanced by the fly-by events, see eq. (5) and the discussion below it. Second, the dynamics of sub-halo mergers in our model slightly favors the formation of massive galaxies at high-z compared to SPF. This is because the cross section we adopt for bound mergers (taken from Menci et al. 2002, eq. 4) is somewhat larger than that used by Somerville, Primack & Faber (2001), especially at high z. In fact, the above authors adopt the cross section derived by Makino & Hut (1997) from N- body simulations, strictly valid for encounters between equal galaxies in the limit of large relative velocities. Our cross section, although reducing to the Makino & Hut's (1997) in the proper limit of merging between equal galaxies with large V_r (as shown in Menci et al. 2002), also holds for lower relative velocities. This is particularly relevant at high $z \gtrsim 4$, when galaxies reside in environments with low velocity dispersions.

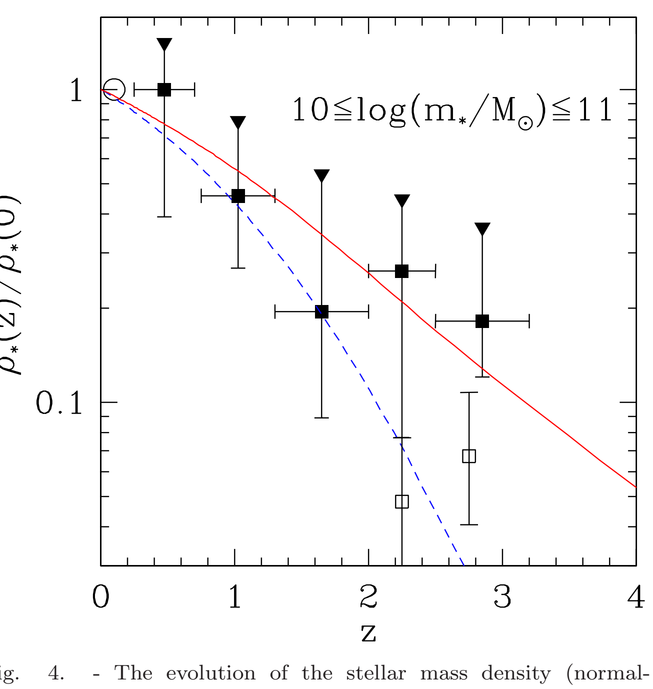

Fig. 4. - The evolution of the stellar mass density (normalized to the present) for galaxies with stellar mass in the range $10^{10}\,M_\odot < m_* < 10^{11}\,M_\odot$ in the starburst mode (red solid line) and in the quiescent mode (blue dashed line) is compared with data from Dickinson et al. (2003, open squares) and from Fontana et al. (2003, solid squares). The triangles show the upper limit obtained on adopting the "maximal mass" algorithm of Fontana et al. (2003b).

The enhancement in the fraction of stars formed in massive galaxies at high redshift $z > 3$ due to our treatment of the bursts is illustrated by fig. (4). There we show for both the burst and the quiescent modes the evolution of the stellar mass density in massive ($10^{10}\,M_\odot < m_* < 10^{11}\,M_\odot$) systems, and compare it with various observations. Although the present data are not sufficient by themselves to discriminate between the two models, the plot clearly shows that at $z \approx 2$ the model with bursts predicts a fraction of stars formed in massive systems which is 2.5 times larger than predicted in the quiescent models.

5. CONCLUSIONS

We have presented the results of a SAM which includes a physical model for starbursts. The latter originate from the destabilization of cold galactic gas occurring in galaxy encounters as described by Cavaliere & Vittorini (2000). In this picture, part of the destabilized gas feeds the accretion onto BHs powering the QSOs (see Menci et al. 2003), while the complementary, larger fraction produces circumnuclear starsbursts at redshifts $z \approx 2 - 4$, preferentially in massive objects. This speeds up the star formation in massive galaxies (favored by their larger cross sections for encounters) at high redshifts (when the higher densities and the slower relative velocities of galaxies in common halos favor strong interactions). The LFs resulting in our model match those of *luminous* ($M_B < -21$) Lyman-break galaxies observed at $z = 3$ and 4, while leaving almost unchanged the model predictions for fainter objects. Thus, at $z \approx 2$, a larger fraction of the stellar content of the massive galaxies is already *in place*, at variance with the predictions of previous hierarchical models; the resulting K-band LFs and z- distributions match the existing data.

Compared to Somerville, Primack, & Faber (2001) our model gives qualitatively similar results, but a better fit (see fig. 3) to the observed z-distribution of bright $K > 20$ galaxies at $z \gtrsim 1.5$. Such a larger rate is mainly due to the novel inclusion of fly-by events which, although producing starbursts with lower efficiency ($f \sim 0.1 - 0.2$ at $z \approx 3$), are more frequent than the bound merging events. In our picture, the UV luminosity, and hence the star formation rate, of massive galaxies at high redshift is in part contributed by the few powerful starbursts occurring in major merging events, and in part by a more widespread, though less powerful, brightening of galaxies almost continuously stimulated by the frequent encounters. In this regime, a considerable fraction close to 0.25 of the present stellar content of massive ($10^{10}\,M_\odot < m_* < 10^{11}\,M_\odot$) galaxies is formed by $z = 2$, see fig. 4. As a result, at lower redshifts $z \approx 1.5$ a considerable fraction of massive galaxies contains a stellar population evolved enough to provide the bright K-band luminosities required to match the observed LFs and counts.

In sum, we have shown that making early massive galaxies takes not only the early collapse of large DM halos favored in the Λ-CDM cosmology, but also baryons forced to shine starlight by galaxy interactions.

We stress that our results are achieved on the basis of a physical – rather than phenomenological – model to derive the burst rate and the amount of cold gas converted into stars during the bursts. Moreover, our model naturally connects with the accretion onto BHs and with the corresponding QSOs emission. Such a unified description is thus able to *link* the independent observations concerning the luminosity distributions of QSOs and of the galaxies.

For $z < 2$ the merging and the encounter rates decline, and no longer affect the evolution of the cold gas reser-

voirs of massive galaxies. So, these galaxies specifically enter a phase of nearly passive evolution, with redder colors which in some cases – whose probability we shall give in detail elsewhere – correspond to those of many observed extremely red objects (EROs see, e.g., Daddi et al. 2002 and references therein). In our model, the beginning and the development of such a phase is naturally matched to the dramatic drop of the QSO luminosities; these are entirely triggered by the gas destabilized in the encounters, and so are particularly sensitive to the current merging and interaction rates of their host galaxies.

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